Search for the Higgs boson in the WW decay channel with the ATLAS Detector

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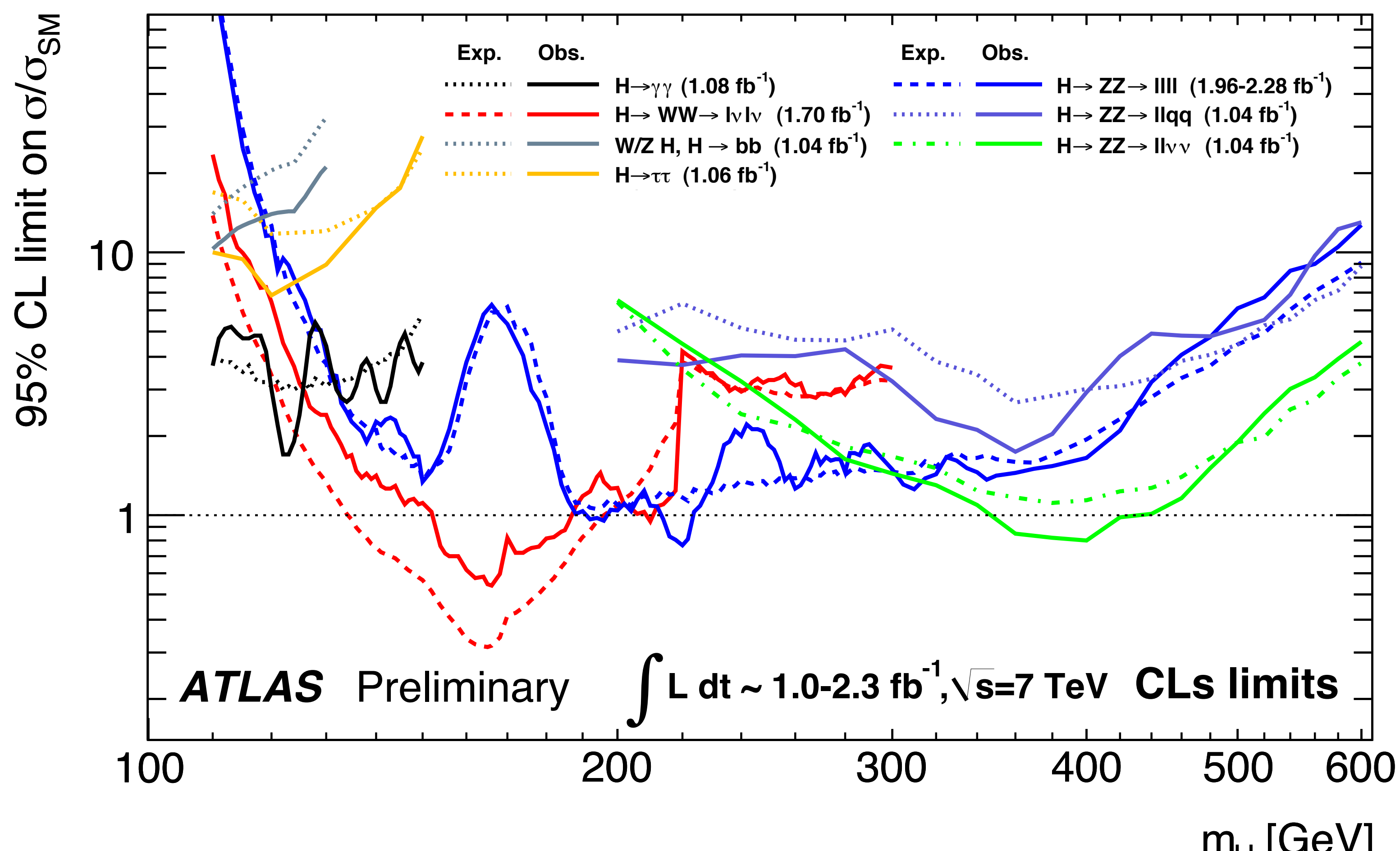
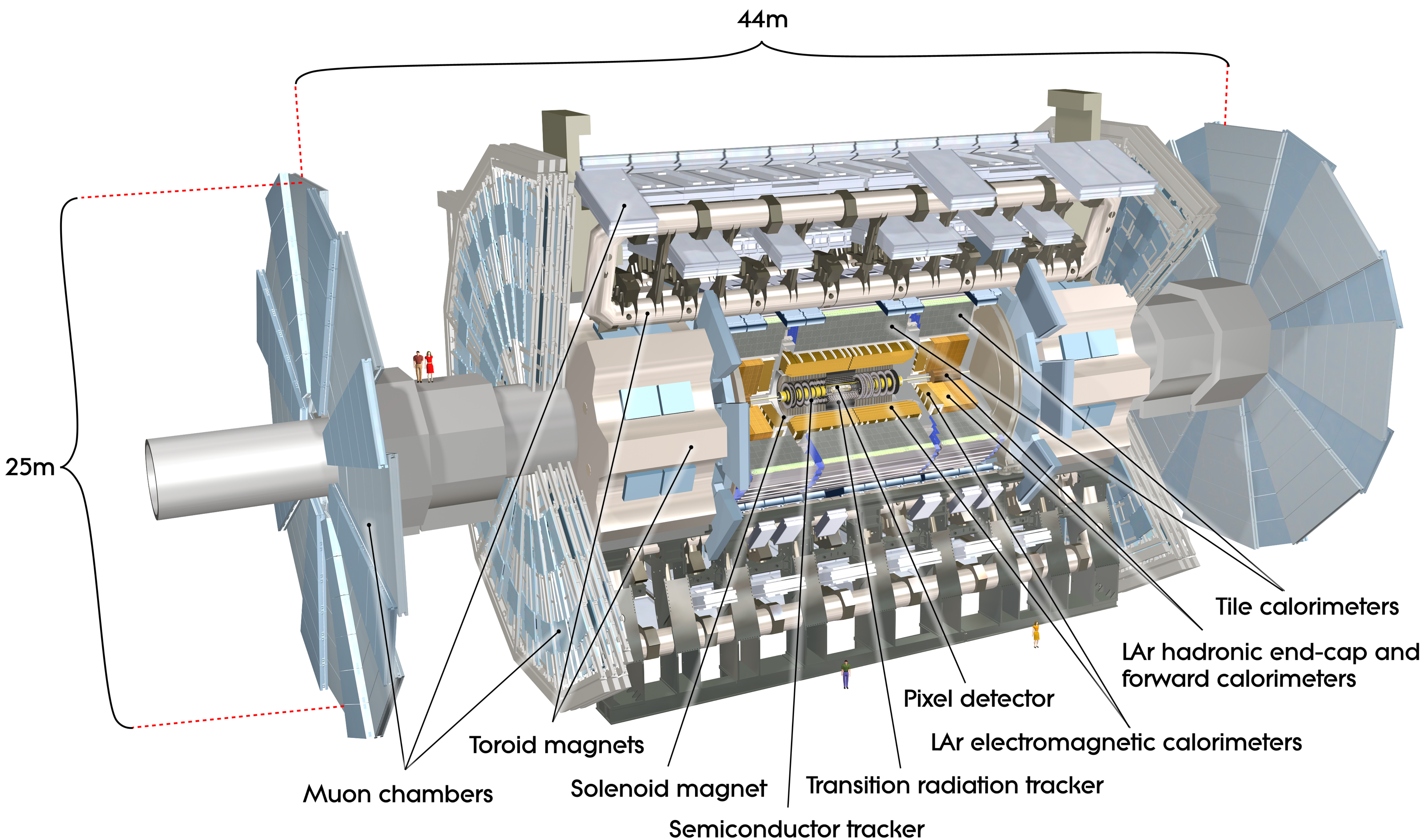
Presented on 1 September 2011
at SUSY 2011 Fermilab, Chicago

Introduction

- LHC searches are rapidly closing in on the SM Higgs boson
  - With 1-2 fb^{-1} of data, ATLAS has sensitivity for $140 < m_H < 410$ GeV
- The $H \to WW$ is particularly sensitive in the intermediate mass range
  - $H \to WW^* \to$ **lνlν** (ee, μμ and eμ) see ATLAS-CONF-2011-134
  - $H \to WW \to$ **lνjj** (e and μ) see ATLAS-CONF-2011-052
- Focus on **lνlν** with an expected exclusion of 135-196 GeV (95% CL) with L=1.7 fb^{-1}



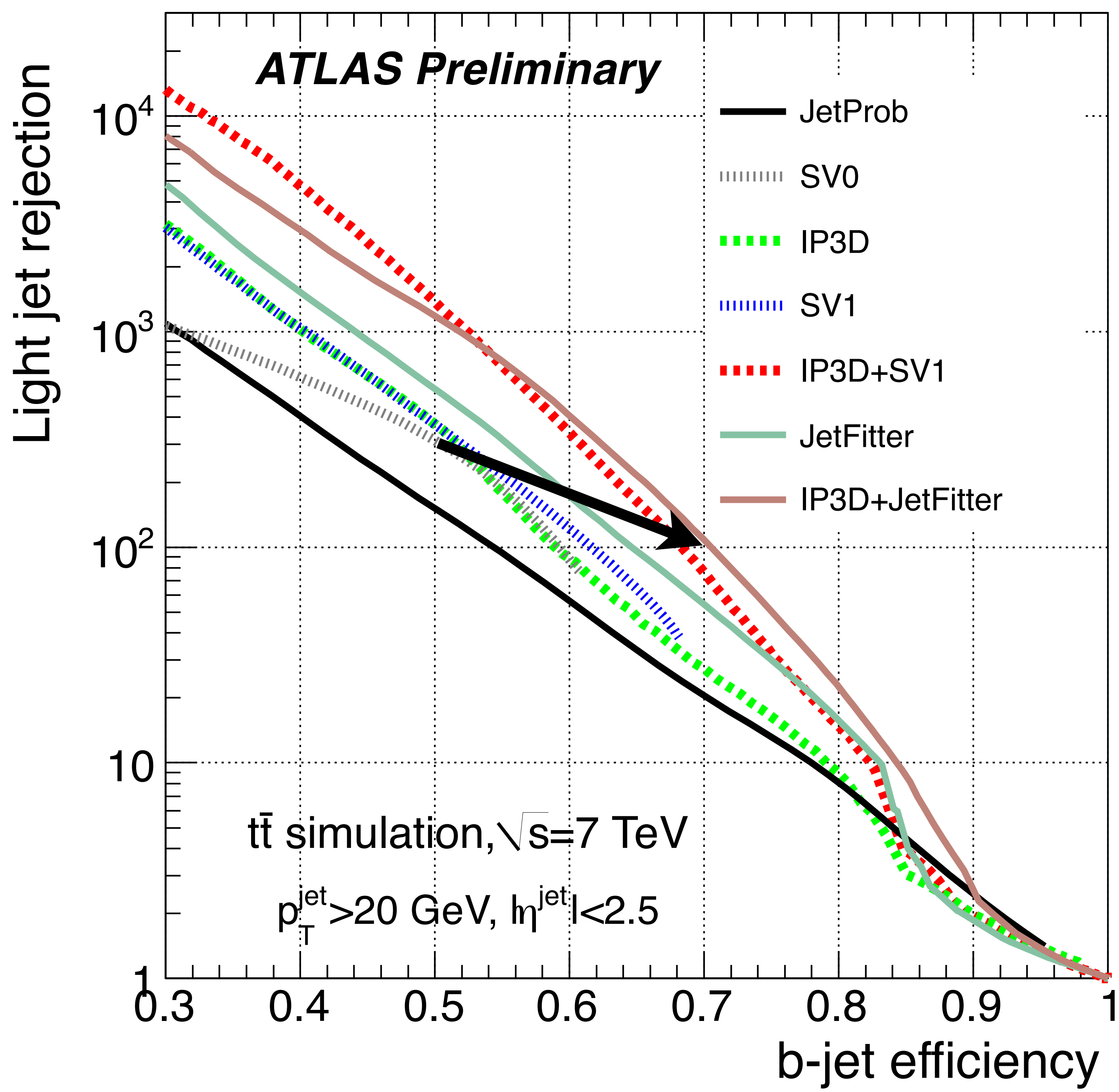
The ATLAS Detector



The H→WW→lνlν Analysis

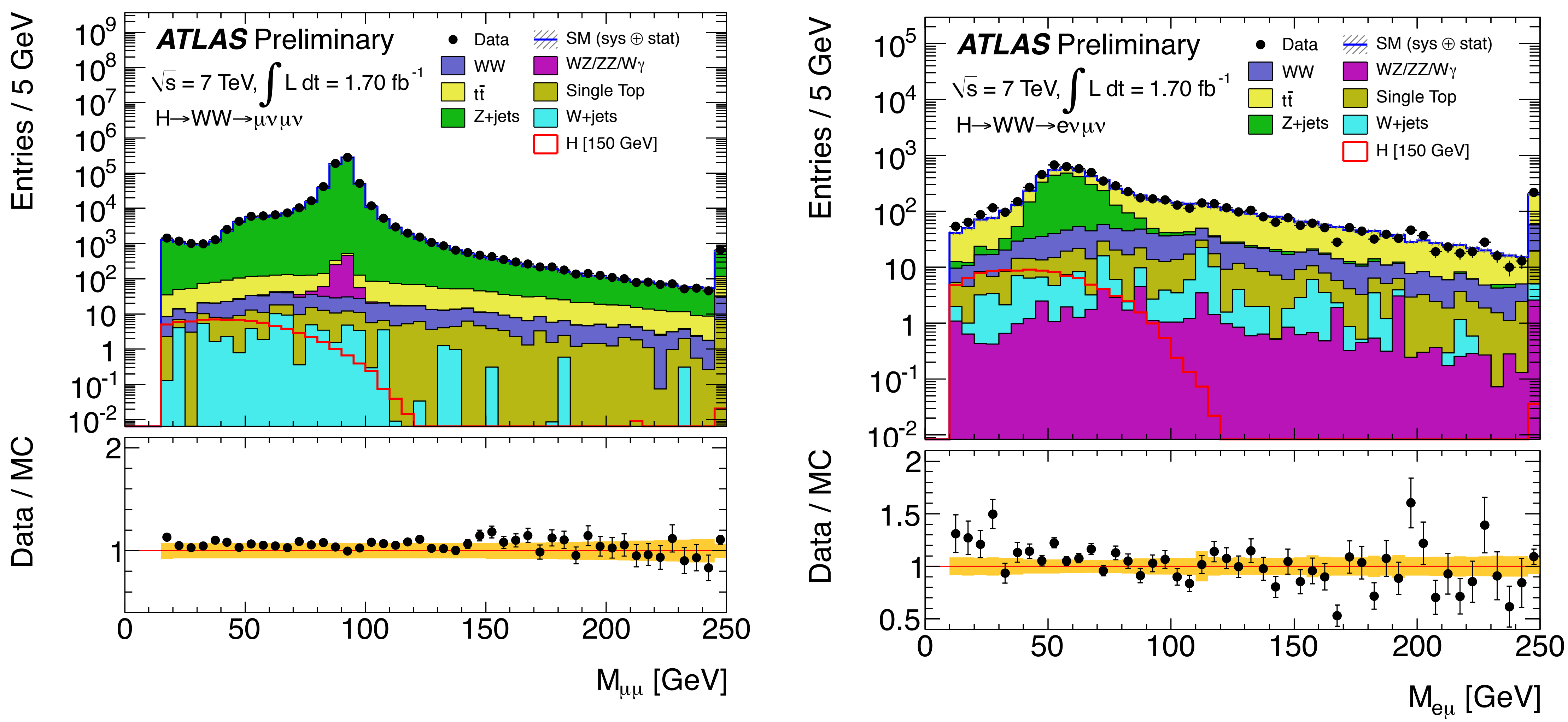
The H→WW→lνlν Analysis

- The H→WW$^{(*)}$→lνlν channel combines the large H→WW branching ratio with a clean final state
  - Analysis performed for 110 < m_H < 300 GeV
- Recently updated to 1.7 fb^{-1}
- Using high performance b-tagging algorithm
- Cuts re-optimised in high mass region: m_H > 220 GeV



Lepton Selection

- Select events containing exactly two opposite sign leptons (e or μ)
- Cut on dilepton invariant mass to reduce Drell-Yan background
  - ee, μμ: $m_{ll} > 15$ GeV, $|m_{ll} - m_Z| > 15$ GeV
  - eμ: $m_{ll} > 10$ GeV
- Note: systematic error bands include normalisation but not shape uncertainty

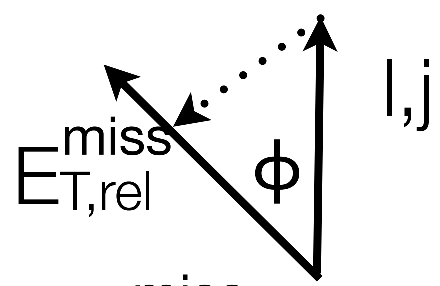


Require large missing energy

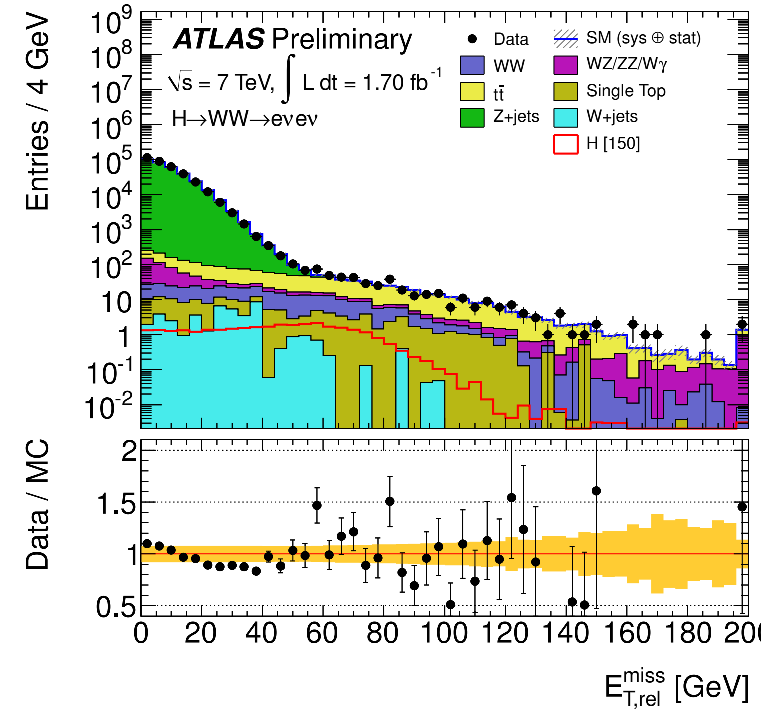
- Require missing energy to suppress QCD and Drell-Yan backgrounds
- Use $E_{T,rel}^{miss}$ instead of $E_{T,miss}$

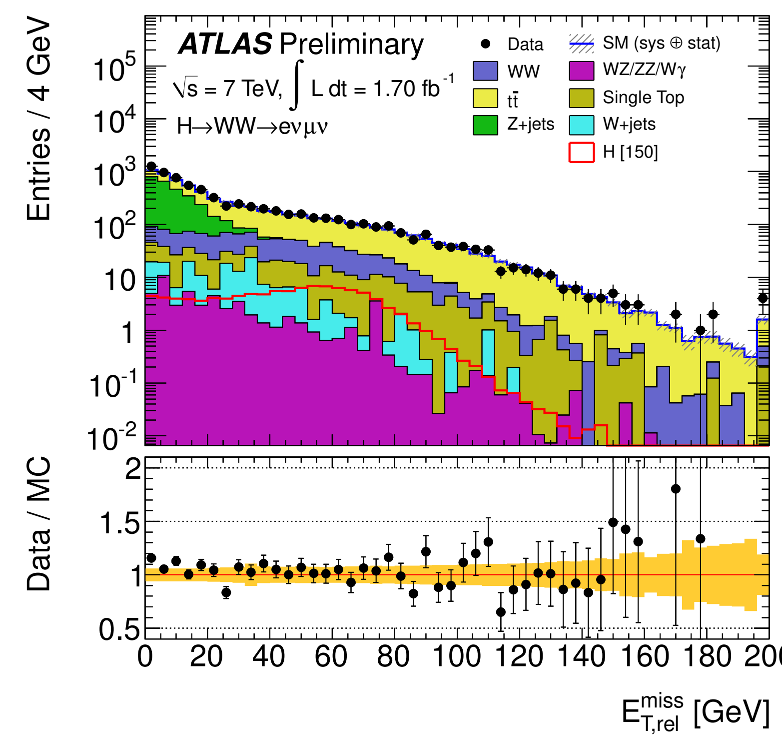
$$E_{\mathrm{T,rel}}^{\mathrm{miss}} = \begin{cases} E_{\mathrm{T}}^{\mathrm{miss}} & \text{if } \Delta\phi \geq \pi/2 \\ E_{\mathrm{T}}^{\mathrm{miss}} \cdot \sin\Delta\phi & \text{if } \Delta\phi < \pi/2 \end{cases}$$

$$\Delta\phi = \min(\Delta\phi(E_T^{\mathrm{miss}}, \ell), \Delta\phi(E_T^{\mathrm{miss}}, j))$$



- Same flavour: $E_{T,rel}^{miss}$ > 40 GeV
- Opposite flavour: $E_{T,rel}^{miss}$ > 25 GeV



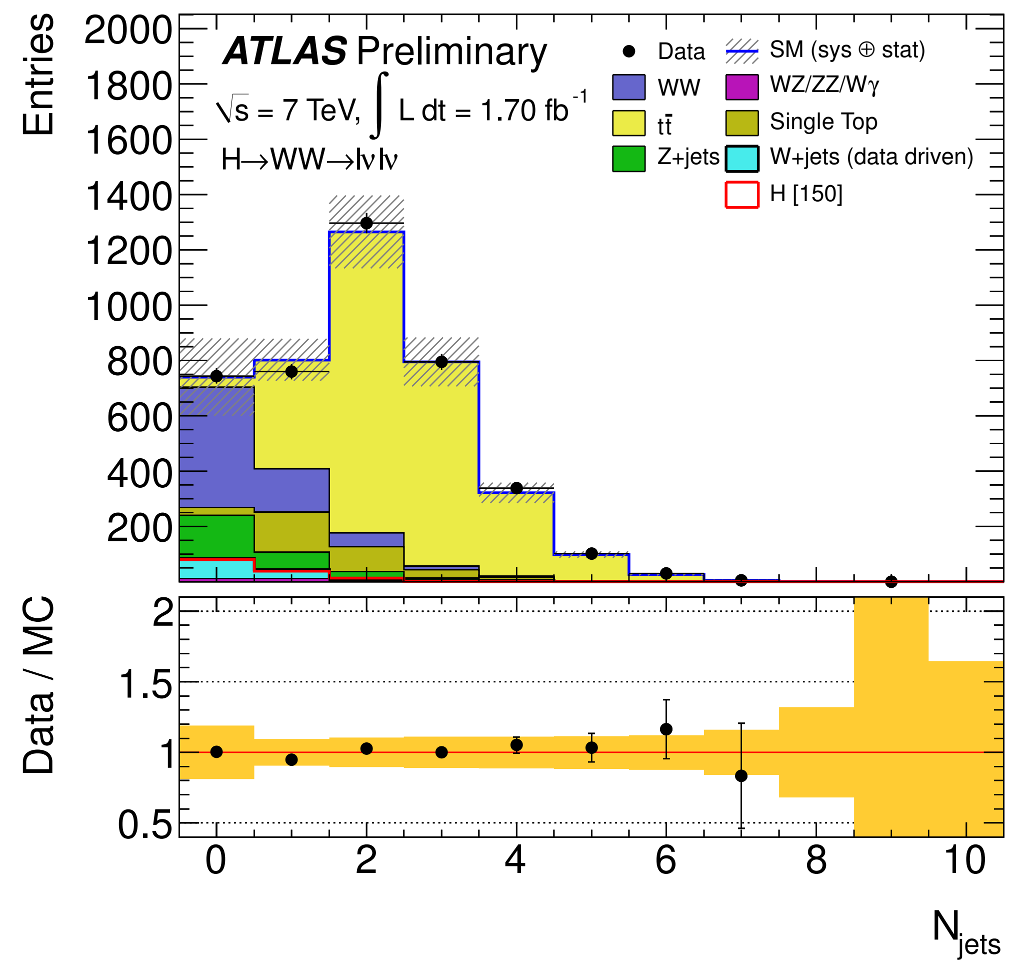


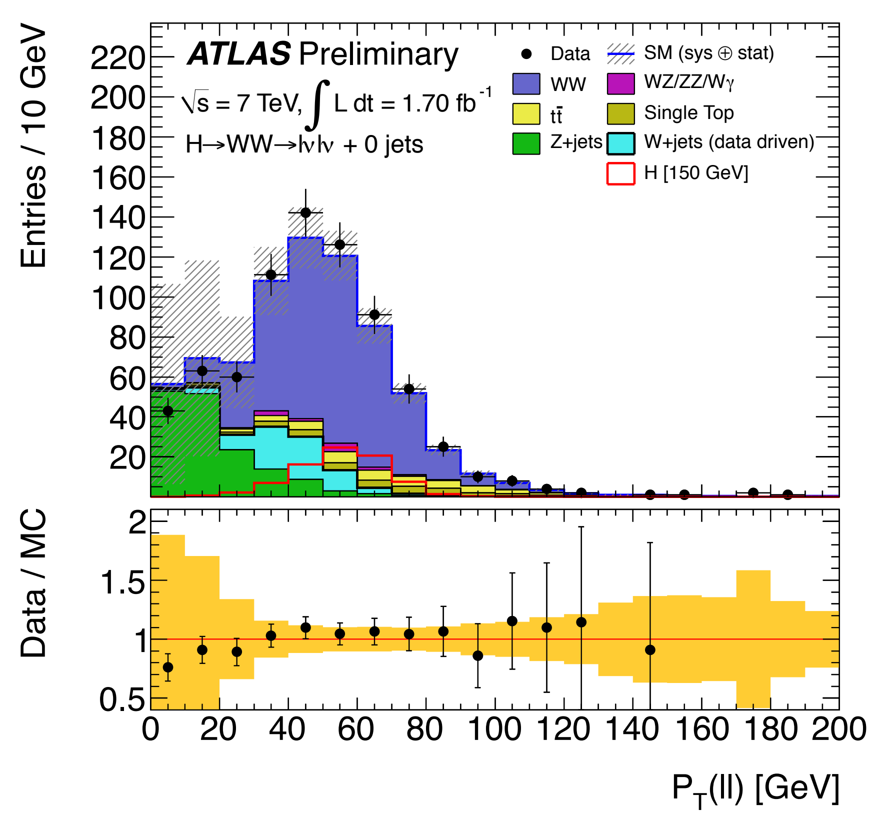
	WW	Z/γ^* + jets	$t\bar{t}$	$tW/tb/tqb$	$WZ/ZZ/W\gamma$	Total Bkg.	Observed
$m_{\ell\ell} > 15$ GeV, $m_{e\mu} > 10$ GeV	1380 ± 100	970000 ± 70000	6200 ± 600	630 ± 70	1200 ± 100	970000 ± 70000	997813
$\lvert m_Z - m_{\ell\ell}\rvert > 15$ GeV	1220 ± 80	91000 ± 7000	5500 ± 600	560 ± 60	92 ± 9	98000 ± 7000	104253
$E_{\mathrm{T,rel}}^{\mathrm{miss}}$	660 ± 50	300 ± 200	2700 ± 300	310 ± 40	28 ± 4	4000 ± 500	4051

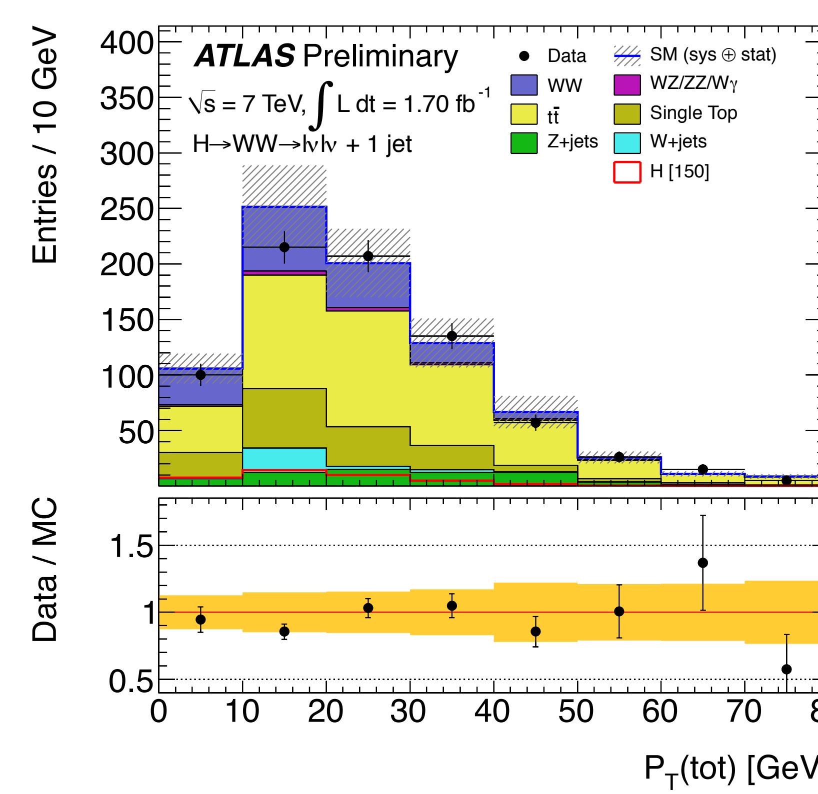
Jet Multiplicity

- Further categorise events by jet multiplicity for jets with $p_T > 25$ GeV, $|\eta| < 4.5$
  - **0j**: Zero jets
  - **1j**: Exactly 1 jet, no b-tag
- Different signal sensitivity and background composition
- Cuts for 0j: Cuts: $p_T^{ll} > 30$ GeV
- Cuts for 1j:
  - no tagged b-jets
  - $p_T^{tot} < 30$ GeV
  - $|m_{\tau\tau} - m_Z| < 25$ GeV

$$\mathbf{p}_T^{tot} = \mathbf{p}_T^{l1} + \mathbf{p}_T^{l2} + \mathbf{p}_T^{j} + \mathbf{p}_T^{miss}$$



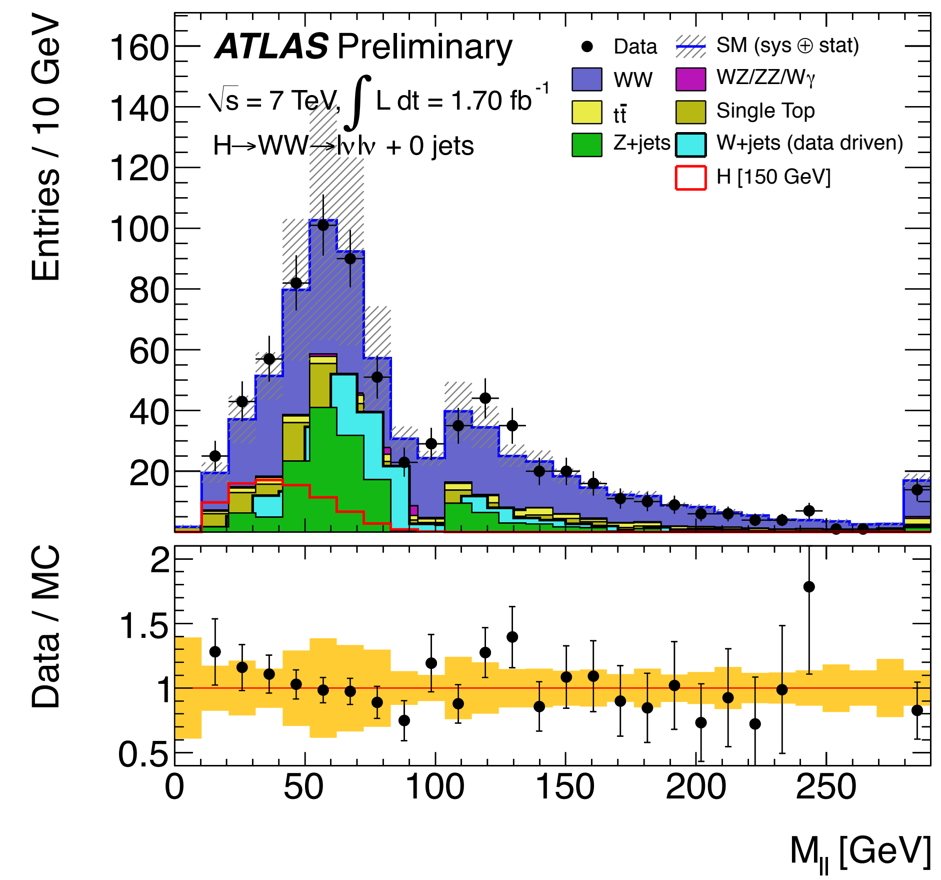


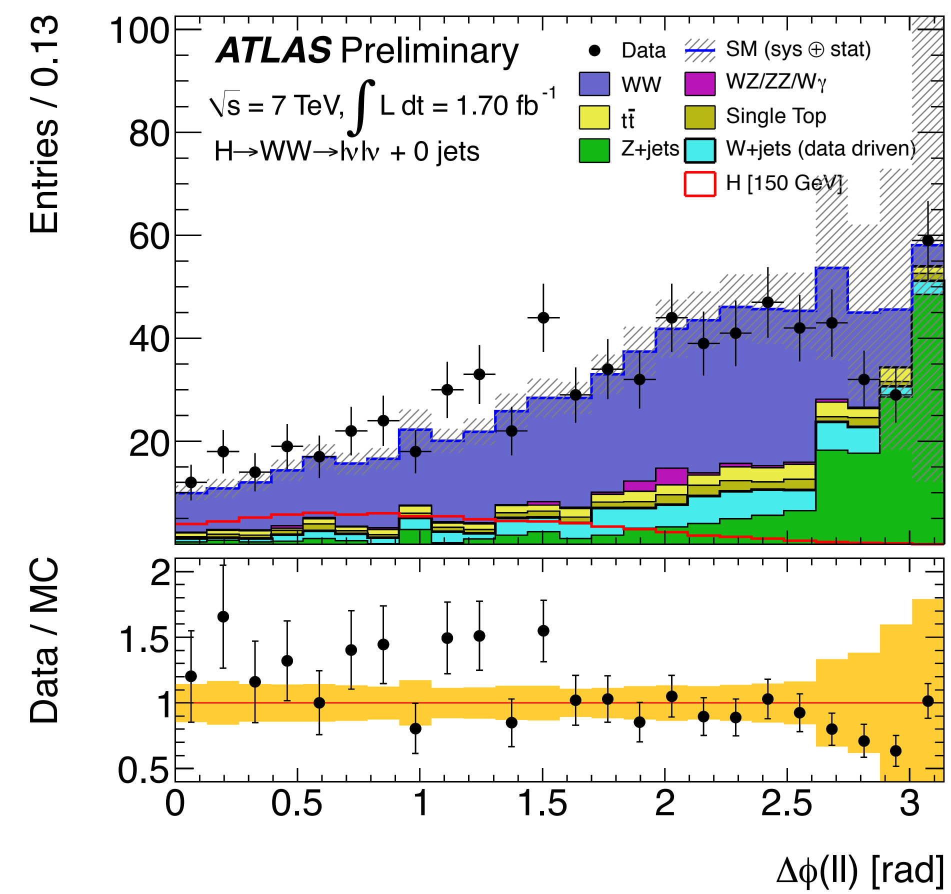


Topological Selection

- Irreducible WW background: topological cuts to exploit Higgs **mass** and **spin**
- Values optimised in 3 Higgs mass ranges
- Dilepton Invariant Mass, $\mathbf{m_{ll}}$
  - m_{ll} < 50 GeV (m_H < 170 GeV)
  - m_{ll} < 65 GeV (170 <= m_H < 220 GeV)
  - 50 < m_{ll} < 180 GeV (m_H >= 220 GeV)
- Opening angle between leptons, $\mathbf{\Delta\phi}$
  - $\Delta\phi$ < 1.3 (m_H < 170 GeV)
  - $\Delta\phi$ < 1.8 (170 <= m_H < 220 GeV)
- Sliding cut on transverse mass, $\mathbf{m_T}$
  - 0.75 m_H < m_T < m_H (m_H < 220 GeV)
  - 0.6 m_H < m_T < m_H (m_H >= 220 GeV)

$$m_T = \sqrt{(E_T^{\ell\ell} + E_T^{\rm miss})^2 - (\mathbf{p}_T^{\ell\ell} + \mathbf{p}_T^{\rm miss})^2}$$





Backgrounds

Backgrounds either partially or fully determined from data

A B C D

Signal$_\alpha$	Control
α	

Signal Region

Higgs

WW

Top

W+jets

WW Control Region

WW

Top

W+jets

$\alpha = N_{MC}^{SR} / N_{MC}^{CR}$

remove $\Delta\phi$ and m_T cuts, tighten m_{ll} cuts

Top Control Region

Top

$\alpha = N_{MC}^{SR} / N_{MC}^{CR}$

1j: remove topological cuts, invert b-jet veto

W+jets Control Region

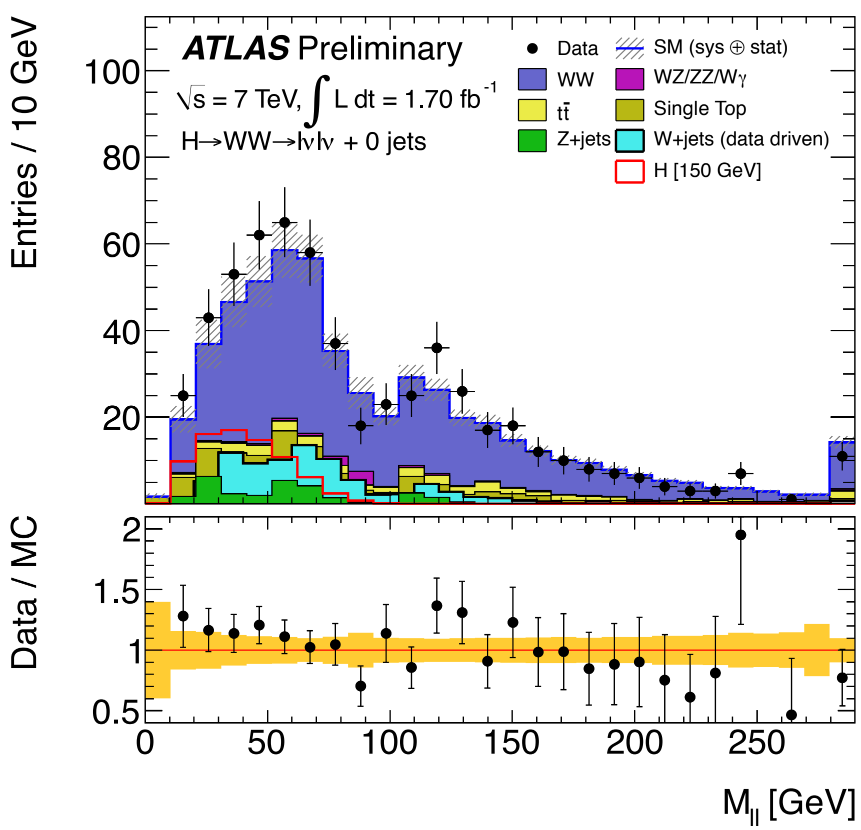
W+jets

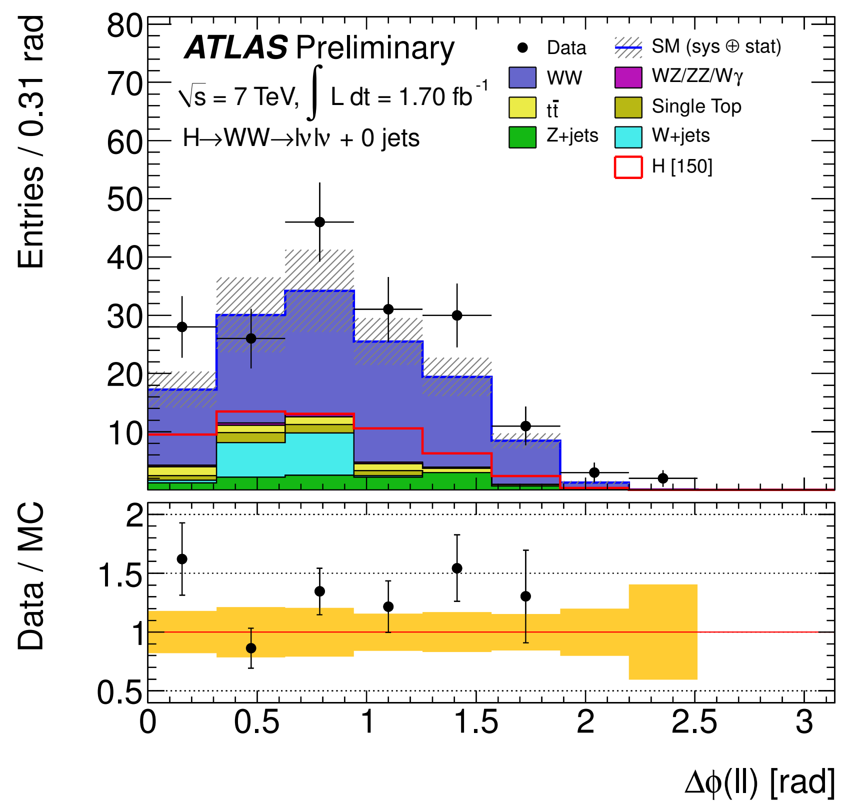
$\alpha = N_{dijet}^{SR} / N_{dijet}^{CR}$

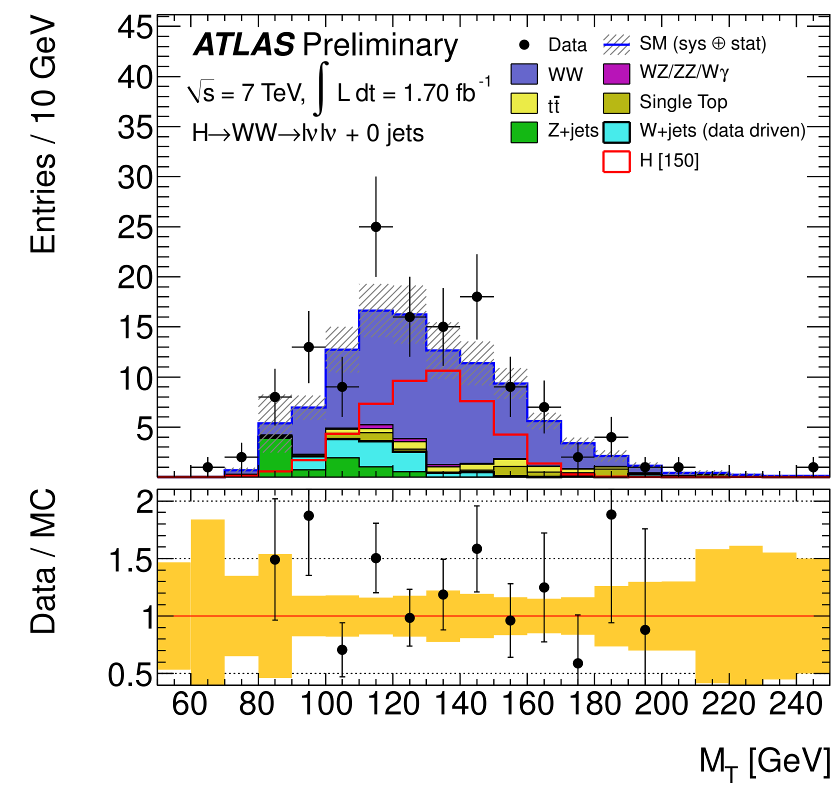
require 2nd lepton to fail tight selection, but pass loose selection

*0j: estimate top background from b-jet survival probability

H→WW→lνlν + 0j



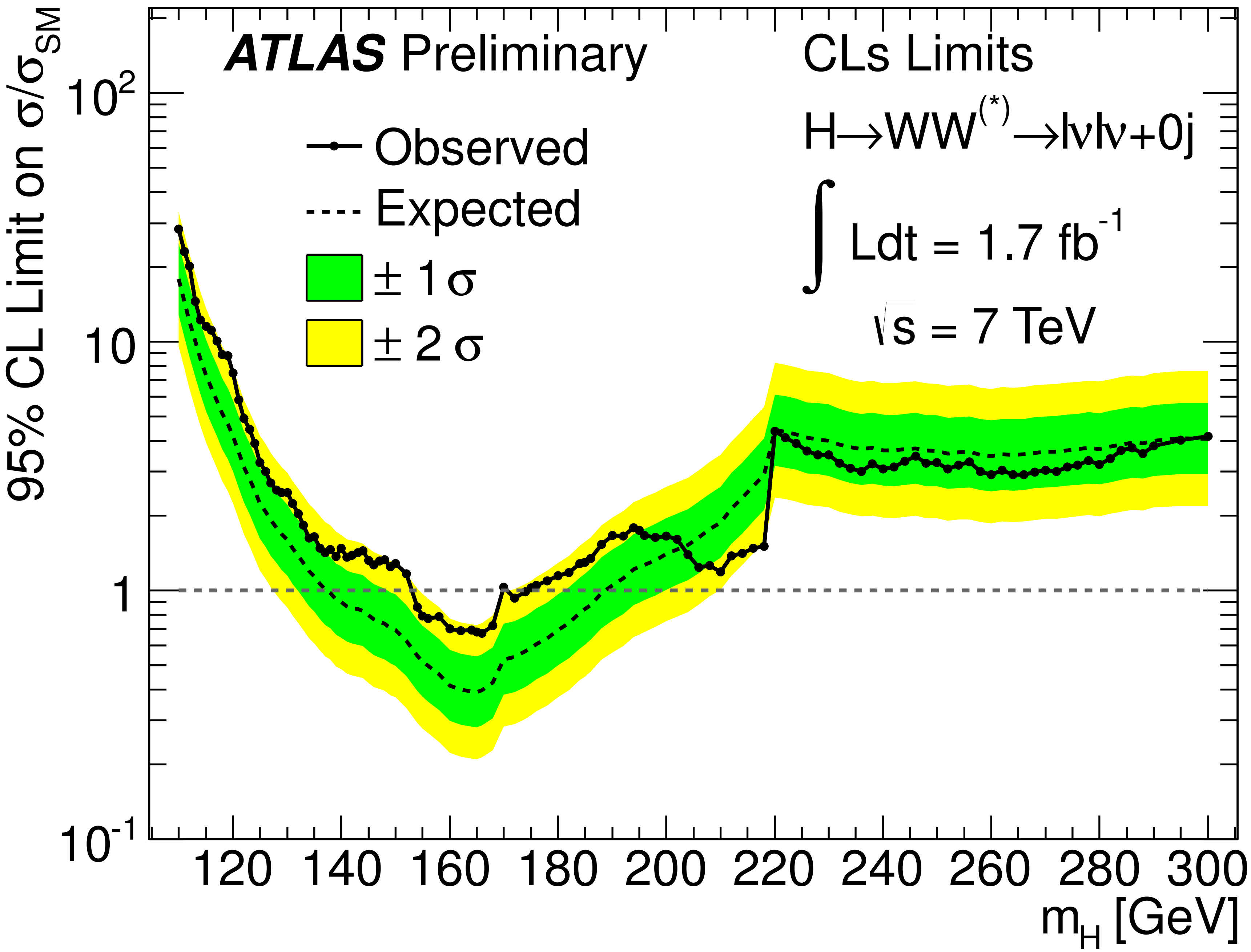




e.g. m_H = 150 GeV

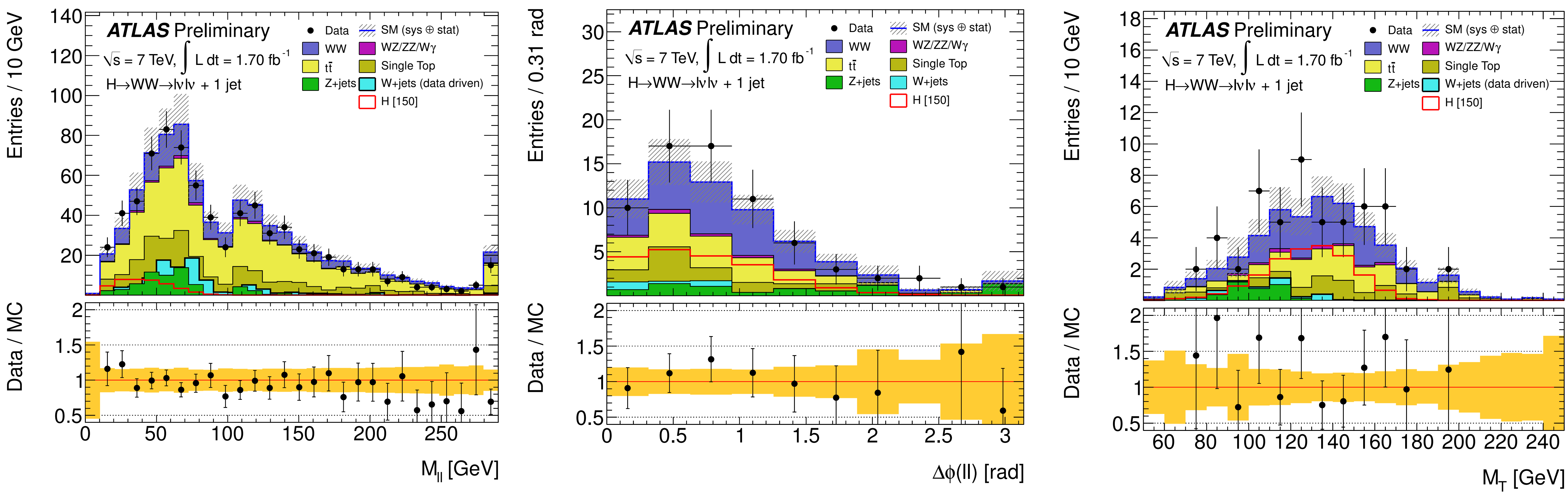
	Signal	WW	$W+$jets	Z/γ^*+jets	$t\bar{t}$	$tW/tb/tqb$	$WZ/ZZ/W\gamma$	Total Bkg.	Observed
Jet Veto	82 ± 17	430 ± 40	70 ± 40	160 ± 150	37 ± 13	28 ± 7	11 ± 3	740 ± 160	738
$\lvert \mathbf{P}_T^{\ell\ell} \rvert > 30$ GeV	79 ± 17	390 ± 40	60 ± 30	28 ± 11	35 ± 12	25 ± 7	10 ± 3	540 ± 80	574
$m_{\ell\ell} < 50$ GeV	56 ± 12	98 ± 13	17 ± 7	12 ± 7	6 ± 3	4.8 ± 1.5	1.2 ± 0.4	139 ± 20	175
$\Delta\phi_{\ell\ell} < 1.3$	48 ± 11	76 ± 10	9 ± 4	8 ± 6	5 ± 2	4.8 ± 1.5	1.1 ± 0.3	105 ± 16	131
$0.75\, m_H < m_T < m_H$	34 ± 7	43 ± 6	5 ± 2	2 ± 4	2.2 ± 1.4	1.2 ± 0.8	0.7 ± 0.3	53 ± 9	70
ee	5.2 ± 1.2	6.2 ± 0.9	0.9 ± 0.4	0.8 ± 1.4	0.3 ± 0.3	0 ± 0.3	0.07 ± 0.05	8.2 ± 1.7	9
$e\mu$	17 ± 4	22 ± 3	2.8 ± 1.3	0 ± 1.3	1.1 ± 0.5	0.8 ± 0.6	0.31 ± 0.19	27 ± 4	32
$\mu\mu$	11 ± 2	14 ± 2	1.0 ± 0.6	1 ± 3	0.8 ± 1.1	0.4 ± 0.4	0.31 ± 0.09	18 ± 5	29

H→WW→lνlν + 0j Limits



- Exclude a range of Higgs masses with the 0j channel alone
- Kink due to cut change at m_H = 220 GeV

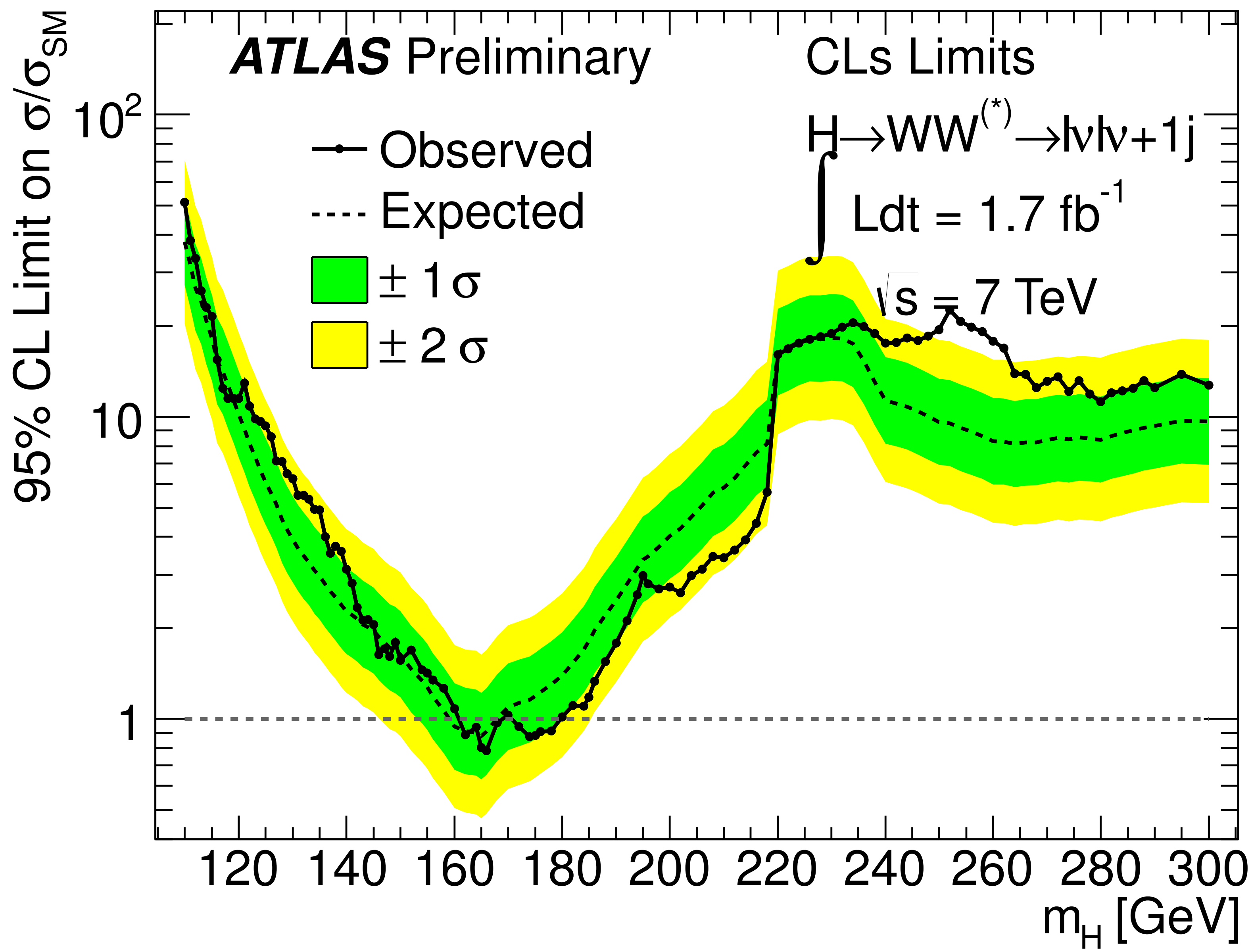
H→WW→lνlν + 1j



e.g. m_H = 150 GeV

	Signal	WW	W + jets	Z/γ^* + jets	$t\bar{t}$	$tW/tb/tqb$	$WZ/ZZ/W\gamma$	Total Bkg.	Observed
1 jet	41 ± 7	158 ± 16	31 ± 19	60 ± 60	390 ± 100	140 ± 20	10.7 ± 1.4	800 ± 120	756
b-jet veto	40 ± 7	154 ± 16	29 ± 18	60 ± 50	140 ± 40	54 ± 9	10.6 ± 1.4	450 ± 70	440
$P_T^{\mathrm{tot}} < 30$ GeV	32 ± 6	127 ± 13	16 ± 9	30 ± 30	90 ± 20	41 ± 7	7.0 ± 0.9	310 ± 50	312
$Z \to \tau\tau$ veto	32 ± 6	124 ± 14	14 ± 7	30 ± 20	84 ± 19	39 ± 7	6.8 ± 1.4	300 ± 30	301
$m_{\ell\ell} < 50$ GeV	22 ± 5	27 ± 5	2.1 ± 1.0	8 ± 6	17 ± 6	9 ± 2	1.5 ± 0.4	64 ± 10	69
$\Delta\phi_{\ell\ell} < 1.3$	19 ± 4	21 ± 4	1.8 ± 0.9	4 ± 5	14 ± 5	8 ± 2	1.2 ± 0.3	50 ± 9	54
$0.75\, m_H < m_T < m_H$	12 ± 3	10 ± 2	0.8 ± 0.4	1.1 ± 1.8	6.9 ± 1.9	3.4 ± 1.4	0.6 ± 0.3	23 ± 4	23
ee	1.7 ± 0.4	1.4 ± 0.4	0.12 ± 0.06	0.07 ± 0.12	0.6 ± 0.3	0.5 ± 0.3	0.10 ± 0.09	2.8 ± 0.7	5
$e\mu$	6.3 ± 1.5	5.7 ± 1.3	0.5 ± 0.3	0.6 ± 1.0	3.7 ± 1.3	2.0 ± 1.0	0.39 ± 0.20	13 ± 3	11
$\mu\mu$	3.9 ± 0.9	3.3 ± 0.7	0.1 ± 0.2	0.5 ± 0.5	2.6 ± 1.5	1.0 ± 0.9	0.08 ± 0.06	8 ± 2	7

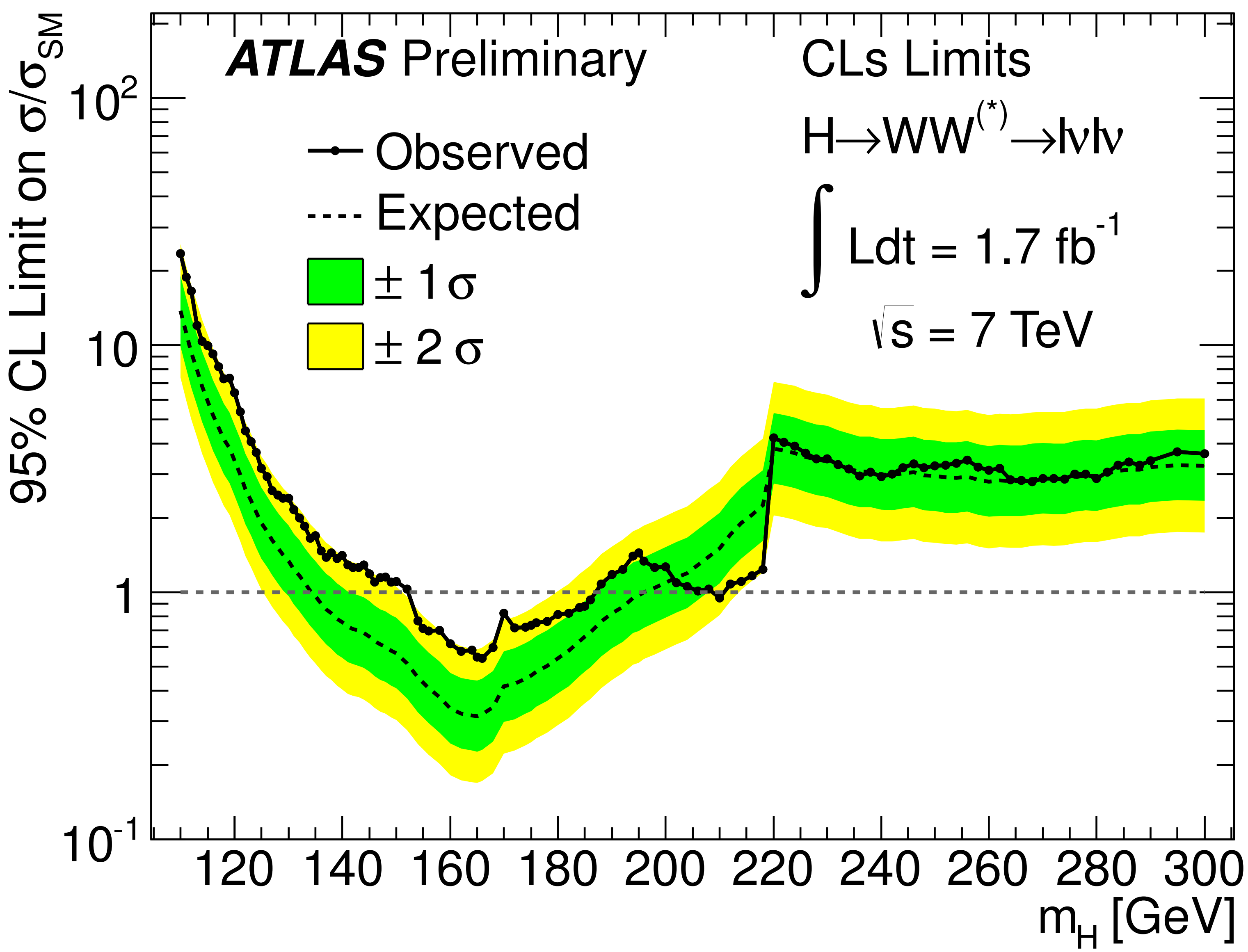
H→WW→lνlν + 1j Limit



- Lower sensitivity than 0j but very close the SM cross-section at m_H = 160 GeV
- Good agreement between the observed and expected limits at low Higgs mass

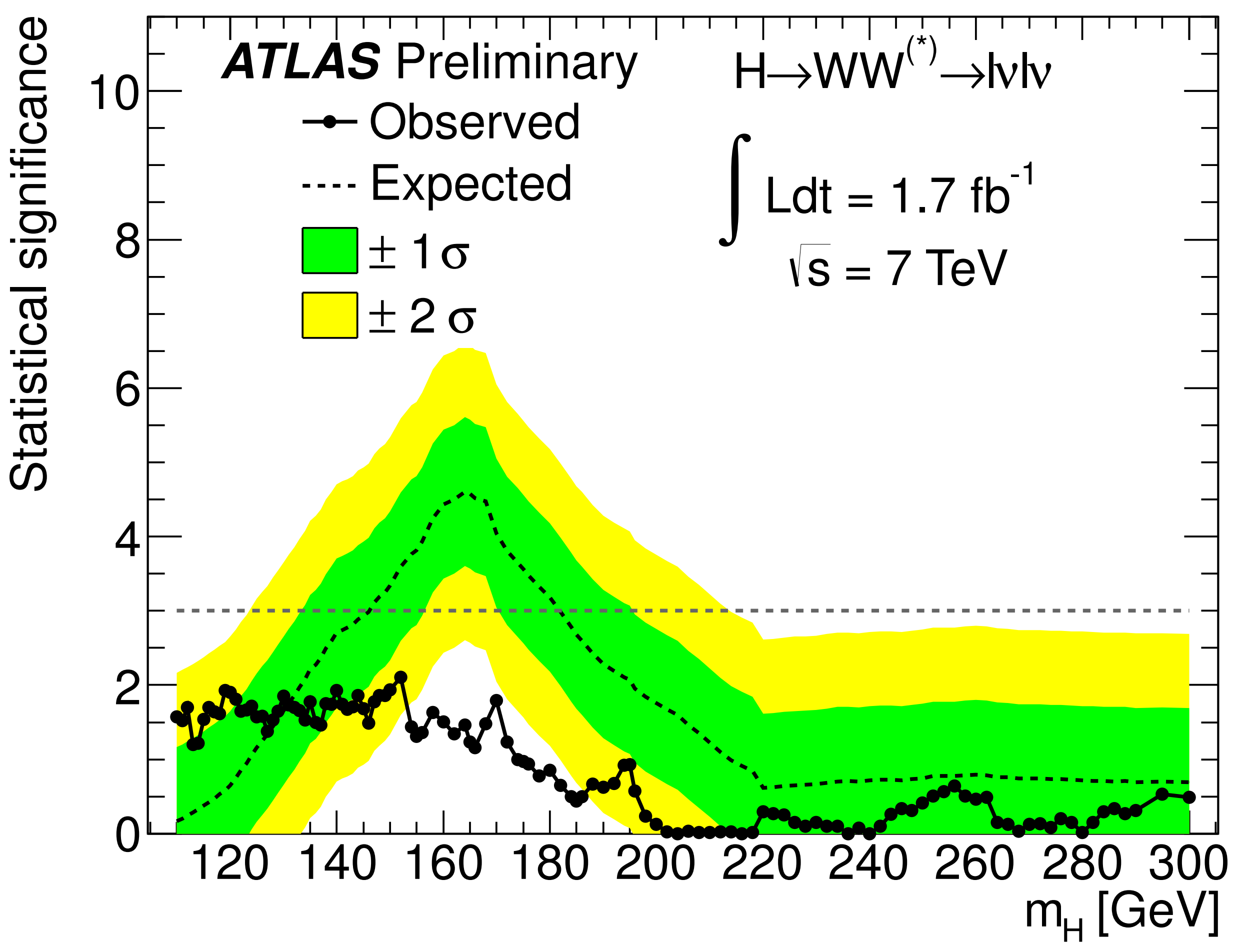
H→WW→lνlν Exclusion Limit

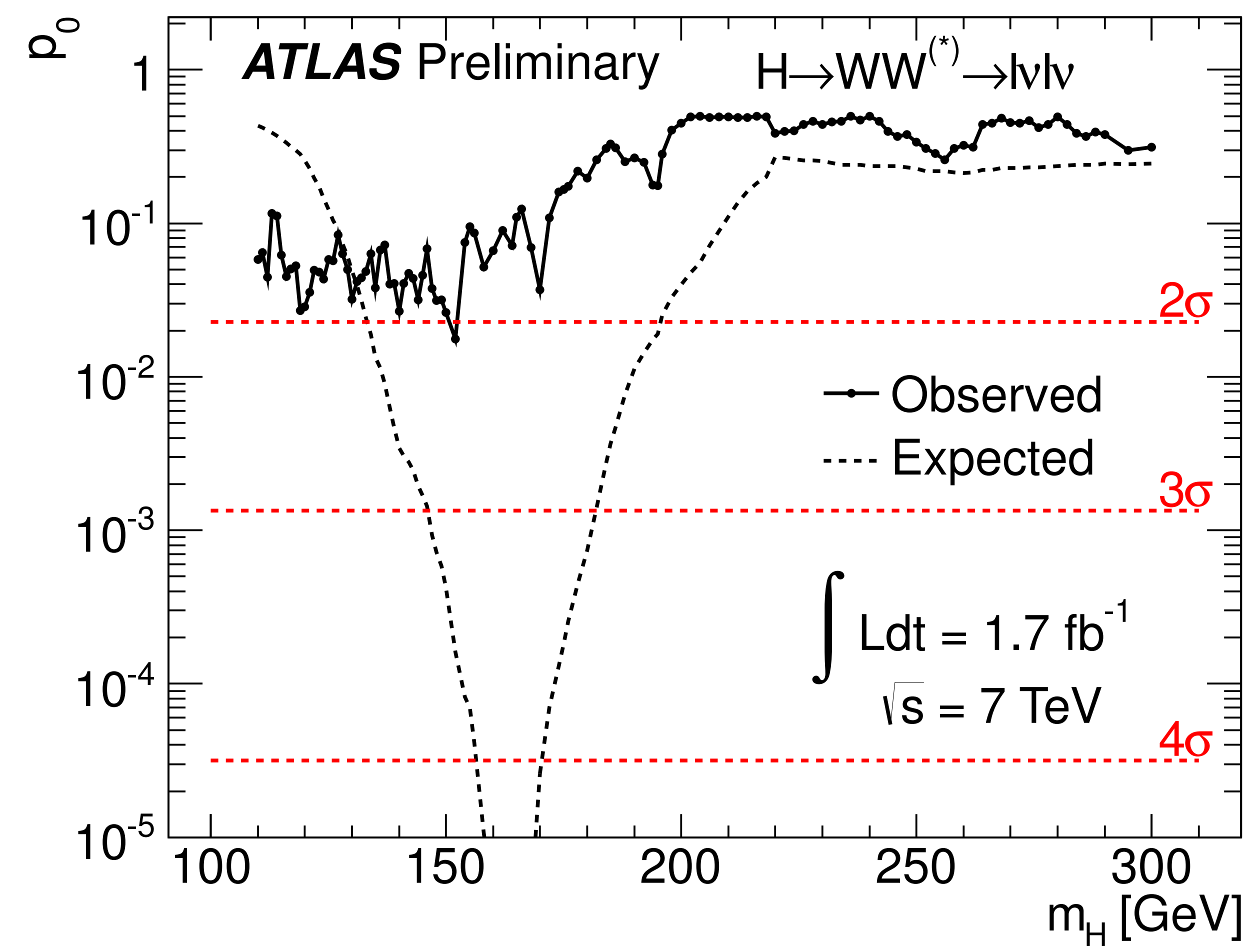
- A SM Higgs boson with **154 < m_H < 186 GeV** is excluded at 95% CL by combining 0j and 1j
  - Expected exclusion range is 135 < m_H < 196 GeV
  - Observed limit is within 2σ of the expected limit over the full range



Significance and p-values

- Compare expected significance as a function of Higgs boson mass to measured significance
- ~2σ excess for m_H < 150 GeV, smaller than that observed with 1 fb^{-1}
- p-value is consistent with background only hypothesis within 2σ





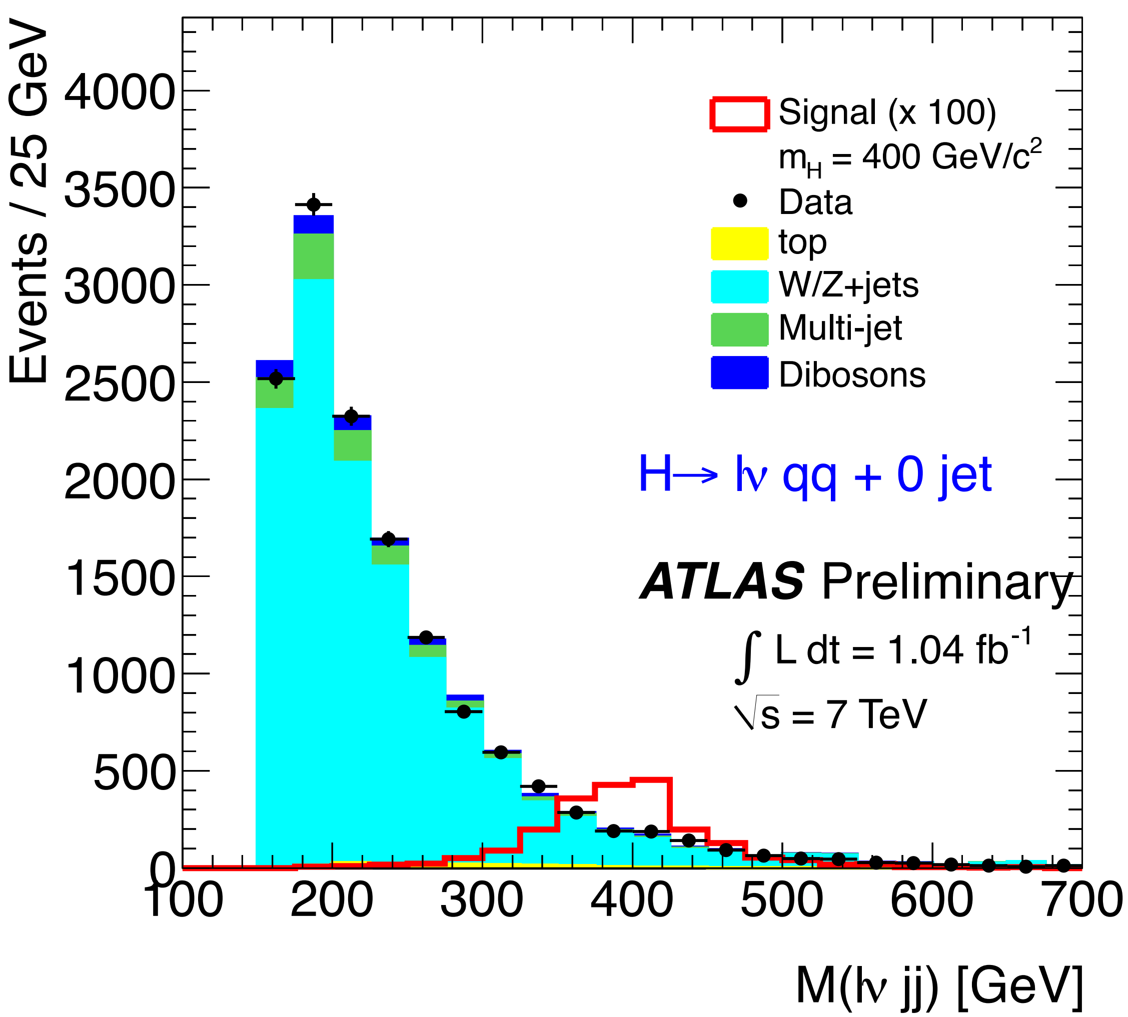
The $H \to WW \to l\nu qq$ Analysis

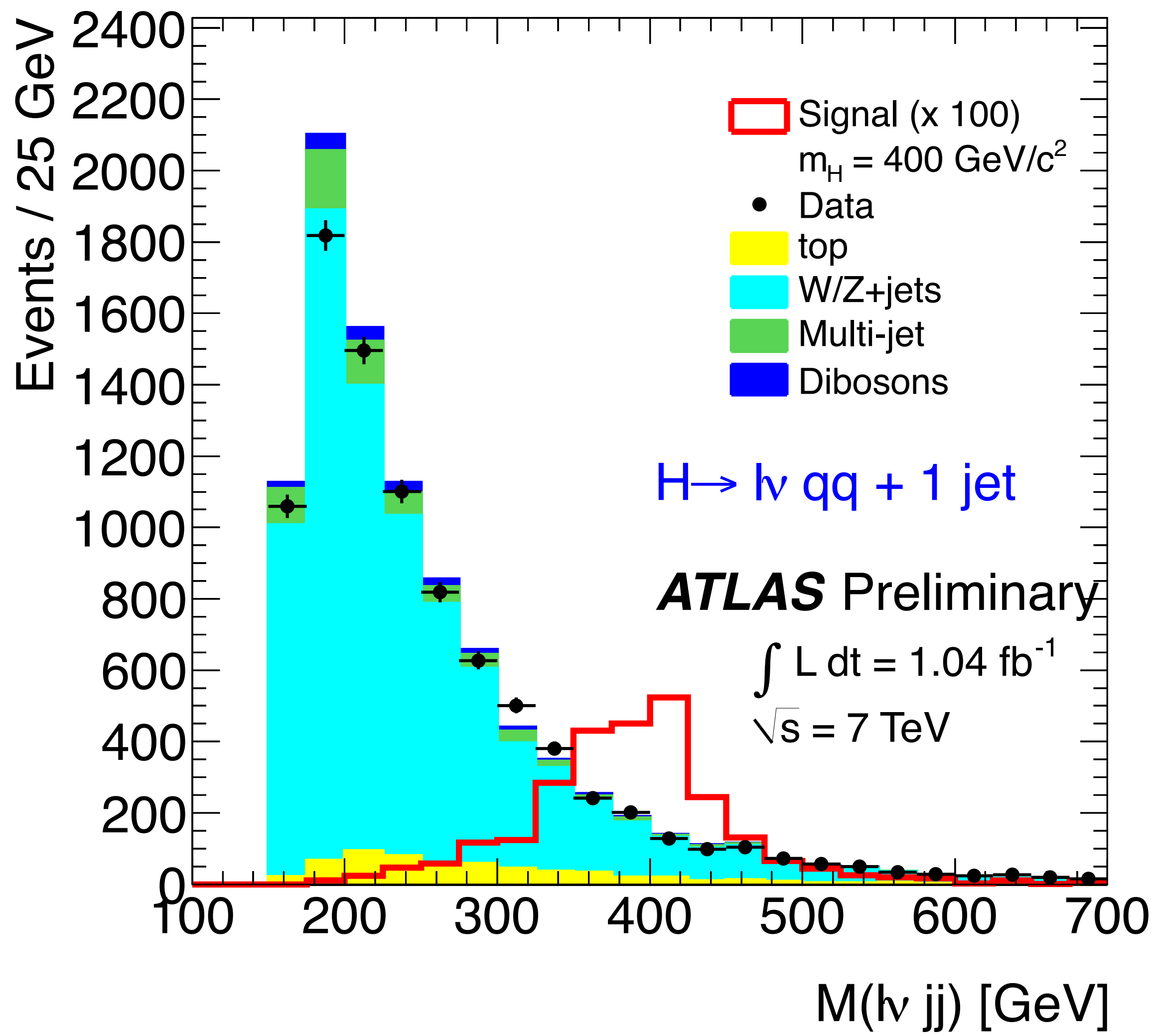
The H→WW→lνqq Analysis

- At larger Higgs mass, it becomes possible to separate the H→WW→lνqq decay from the large backgrounds
- Analysis performed for **240 GeV** < m_H < **600 GeV**
  - Greatest sensitivity for m_H = 500 GeV
- Select events containing **one lepton**, **large E_T^{miss}** and **jets**
  - Exactly **one lepton** (e, μ) with **p_T > 30 GeV**
  - **E_T^{miss} > 30 GeV**
  - Either **2** or **3 jets** with **p_T > 25 GeV** within $|\eta| < 2.4$
  - Two jets with 71 < M_{jj} < 91 GeV
  - **Veto** events if any jet is **b-tagged**
- Reconstruct Higgs mass ($M_{l\nu qq}$) by imposing **$M_{l\nu}$=M_W** and **M_{qq}=M_W**
  - Search for bump in the $M_{l\nu qq}$ distribution above the strongly falling background

Selection and Mass Distributions

	$H(e\nu qq)$ + 0j	$H(\mu\nu qq)$ + 0j	$H(e\nu qq)$ + 1j	$H(\mu\nu qq)$ + 1j	H + 0j or 1j
W/Z+jets	10780 ± 290	13380 ± 870	6510 ± 250	7410 ± 670	38080 ± 1170
Multi-jet	890 ± 24	256 ± 17	669 ± 25	212 ± 19	2027 ± 43
Top	170 ± 34	164 ± 33	489 ± 98	500 ± 100	1330 ± 270
Dibosons	397 ± 79	414 ± 83	161 ± 32	204 ± 41	1180 ± 240
Total Background	12240 ± 300	14210 ± 870	7830 ± 270	8330 ± 680	$\boxed{42600 \pm 1200}$
Observed	11988	13906	7543	8250	$\boxed{41687}$
Signal (400 GeV)	14 ± 3.6	12 ± 3.1	18 ± 4.7	14 ± 3.6	58 ± 15

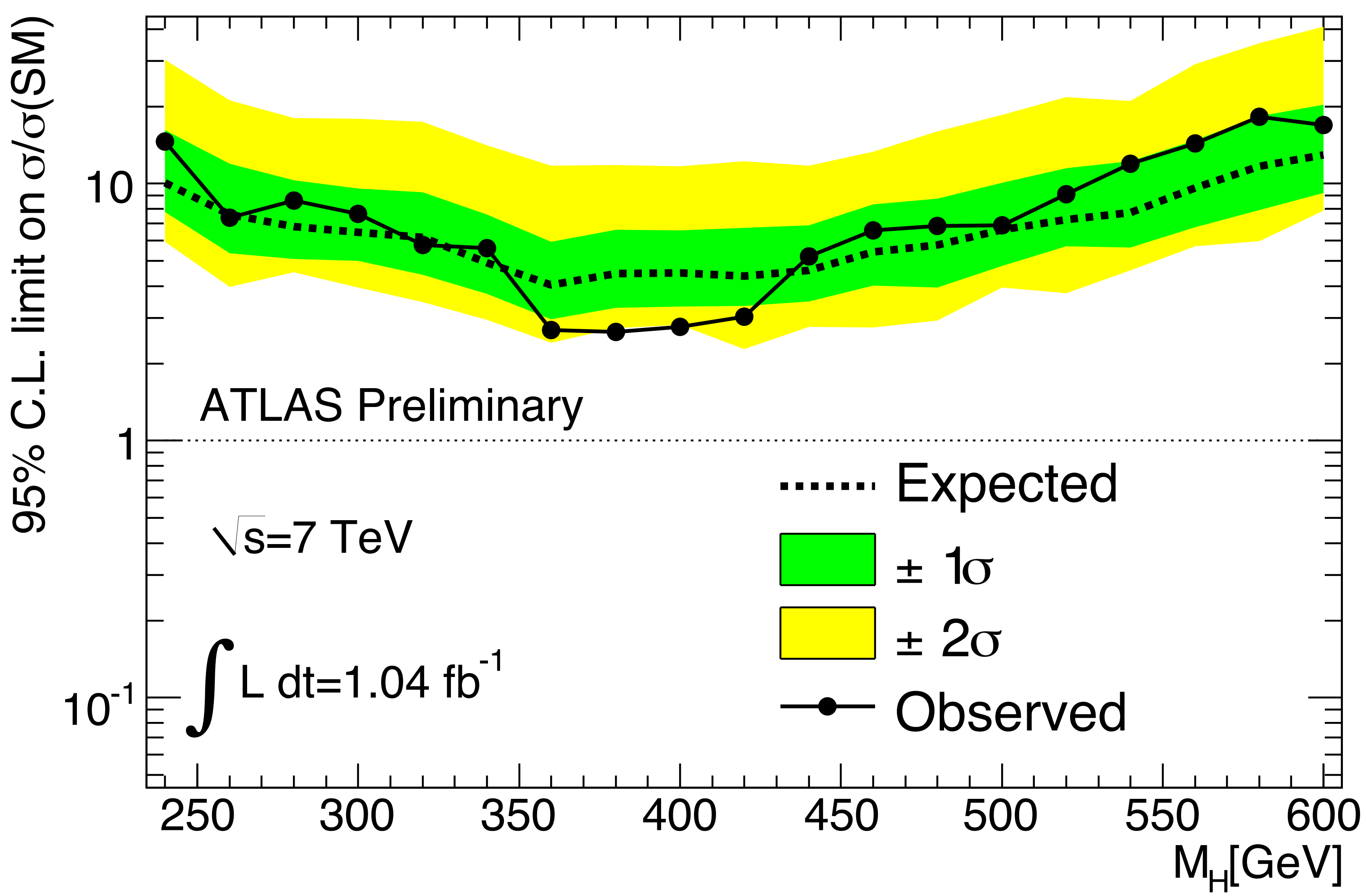




Dominant backgrounds are W/Z+jets

The H→WW→lνqq Exclusion Limit

- Signal extracted using a maximum likelihood fit to the background modelled by the sum of two exponentials
- For **350 < m_H < 420 GeV**, the 95% CL is ~2.7 x SM cross-section
- Expected limit in this range is ~4 x SM cross-section



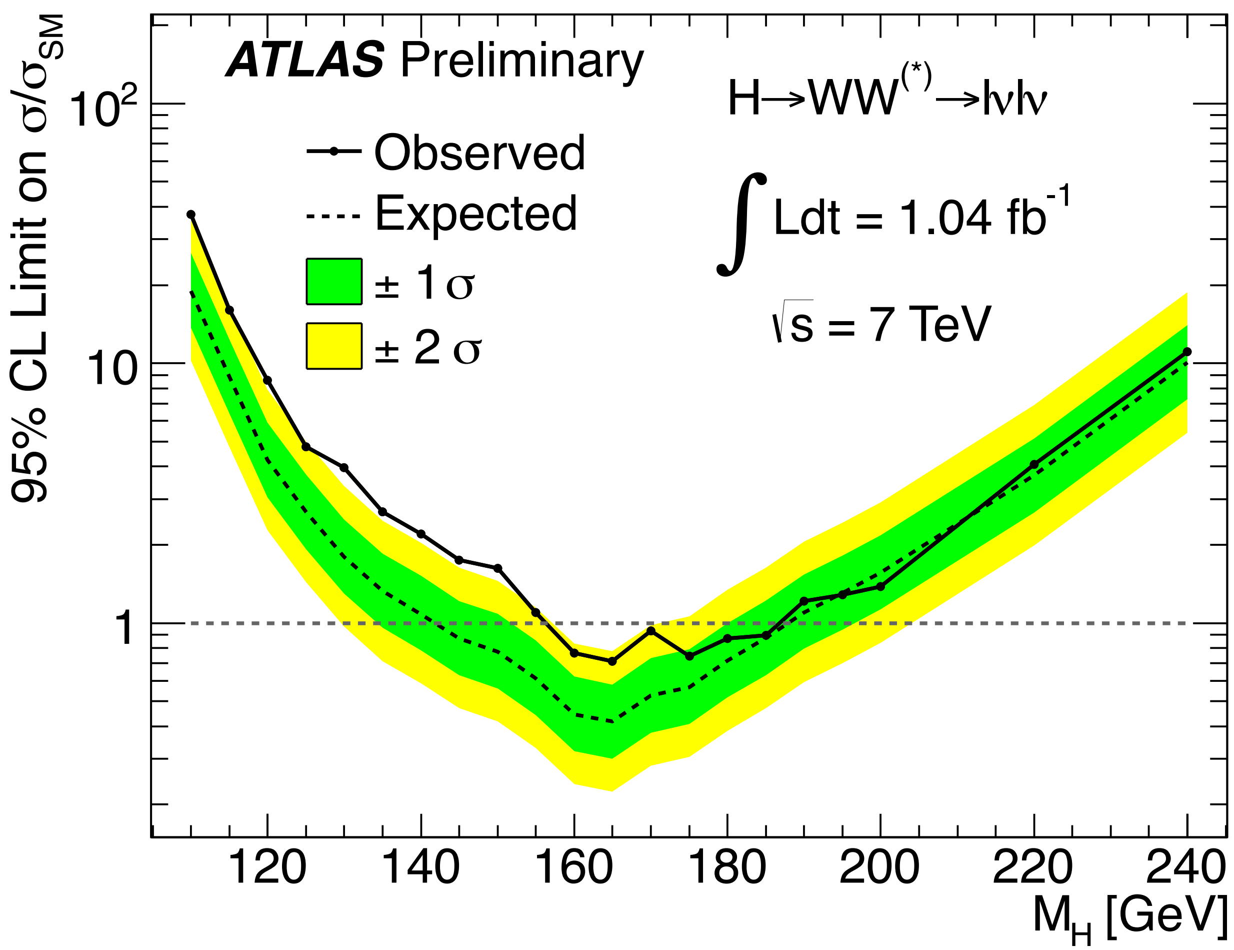
Conclusions

- Presented latest results from ATLAS in the $H \to WW \to l\nu l\nu$ and $H \to WW \to l\nu qq$ channels
  - **No evidence** (yet) for the Higgs boson
  - **$H \to WW \to l\nu l\nu$** analysis excludes the SM Higgs for **$154 < m_H < 186$ GeV** at 95% CL
    - cf. expected exclusion range: $135 < m_H < 196$ GeV
  - **$H \to WW \to l\nu qq$** channel obtains a limit of **$\sim 2.7\sigma_{SM}$**
- A small deviation of ~2σ between the expected and observed limits is observed in the range $110 < m_H < 150$ GeV in the $H \to WW \to l\nu l\nu$ analysis
  - Neighbouring mass points are highly correlated due to the mass resolution
- Stay tuned as we close in on the SM Higgs boson!

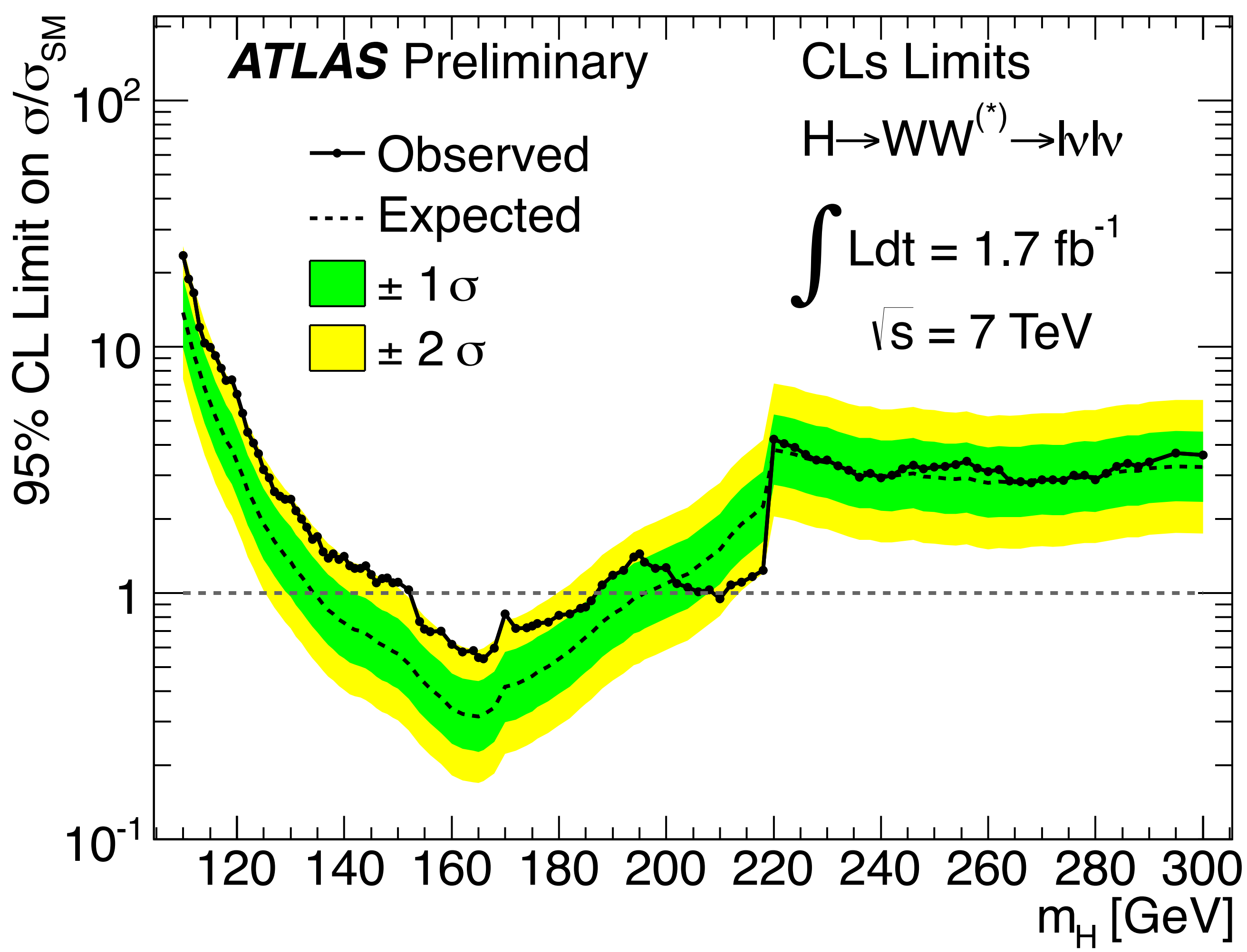
Back up

H→WW→lνlν in 2011

EPS



Lepton-Photon



Systematic Uncertainties

Source of Uncertainty	Treatment in the analysis
Jet Energy Resolution (JER)	$\sim$ 14%, see Ref. [69]
Jet Energy Scale (JES)	Takes into account close-by jets effect, jet flavor composition uncertainty
	and event pile-up uncertainty in addition to global JES uncertainty
	Global JES $< 10\%$ for $p_{\mathrm{T}} > 15$ GeV and $\|\eta\| < 4.5$, see Ref. [70]
	Pile-up uncertainty 2-5% for $\|\eta\| < 2.1$ and 3-7% for $2.1 < \|\eta\| < 4.5$
	These are summed in quadrature before application.
Electron Selection Efficiency	Separate systematics for electron identification,
	reconstruction and isolation, added in quadrature
	Total uncertainty of 2-5% depending on η and E_T
Electron Energy Scale	Uncertainty smaller than 1%, depending on η and E_T
Electron Energy Resolution	Energy varied within its uncertainty, 0.6% of the energy at most
Muon Selection Efficiency	0.3-1% as a function of η and p_{T}
Muon Momentum Scale	η dependent scale offset in p_{T}, up to $\sim 0.13\%$
Muon Momentum Resolution	p_{T} and η dependent resolution smearing functions, $\leq 5\%$
b-tagging Efficiency	p_{T} dependent scale factor uncertainties, 5.6-15%, see Ref. [71]
b-tagging Mis-tag Rate	up to 21% as a function of p_{T}, see Ref. [71]
Missing Transverse Energy	13.2% uncertainty on topological cluster energy
	Electron and muon p_{T} changes from smearing propagated to MET
	Effect of out-of-time pileup: MET smeared by 5 GeV in 1/3 of MC events
Luminosity	3.7% [25]

$Z \rightarrow \tau\tau$ Rejection

- Reconstruction $m_{\tau\tau}$ by assuming
  - leptons arise from $Z \rightarrow \tau\tau$ decays
  - neutrinos are collinear with the leptons
- Reject the event when
  - the energy fractions of the visible decay products are positive
    - i.e. $x_{\tau 1} > 0$ and $x_{\tau 2} > 0$
  - and the invariant mass is consistent with the Z
    - i.e. $|m_{\tau\tau} - M_Z| < 25$ GeV
- Only applied in H + 1j, because in H+0j the leptons are more often back-to-back